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Procedia Engineering 25 (2011) 864 – 867

Procedia Engineering

www.elsevier.com/locate/procedia

Proc. Eurosensors XXV, September 4-7, 2011, Athens, Greece

Investigation of triple-junction photodetector in 90 nm CMOS technology

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Abstract

A triple-junction photodetector for color detection is explored in the wavelength range from 400 nm to 900 nm. According to the mechanism that light with longer wavelength can penetrate silicon deeper than light with shorter wavelength the detector can detect different colors of incident light simultaneously and rather independently. We adopt three vertically stacked photodiodes in the detector, which accurately determine the color of the incident light. In addition, the photodetector can be used as wavelengths division demultiplexer for three different wavelengths in optical data receivers without needing beam splitters or optical filters. The detector is fabricated in a standard 90 nm CMOS technology without any process modifications. Based on the measured results, we conclude that this kind of photodetector can meet the requirements of color detection and of data receivers up to150 Mbit/s.

Keywords: photodetector; color detector; triple-junction; vertical; penetration depth; CMOS

1. Motivation

Most conventional photodetectors use an array of at least three laterally arranged photodiodes covered with a mosaic of different color filters (so-called Bayer filters). These color filters are needed because normal photodiodes can only detect light intensity but have no color selectivity. Each of the three diodes is covered by a certain optical filter and records only one distinct color. The color of the incident light is determined by combining the three output signals. Major drawbacks of such photodetectors are the increased silicon area due to the three laterally arranged photodiodes and the need of additional color

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doi:10.1016/j.proeng.2011.12.212

filters which lead to additional nonstandard production steps in ASIC foundries. Both lead to increased production costs [1]. On the other hand, some kinds of triple-junction structure are implemented in BiCMOS technology [2]. Since BiCMOS technology is more complicated than CMOS technology, the fabrication costs are also increased.

The triple-junction photodetector in 90 nm CMOS technology overcomes these disadvantages. It is built up of three vertically arranged photodiodes and uses the wavelength dependent penetration depth of light in silicon to achieve color selectivity. The three pn junctions collect the carriers which are generated by the incident light in a wavelength dependent depth from the semiconductor surface. The advantages of this structure are the decreased silicon area, the use of a standard 90 nm CMOS technology without additional optical filters or metal gratings, as described in [3] and [4], and the possibility to integrate the sensor with other CMOS circuitry onto a single die.

2. Working principle

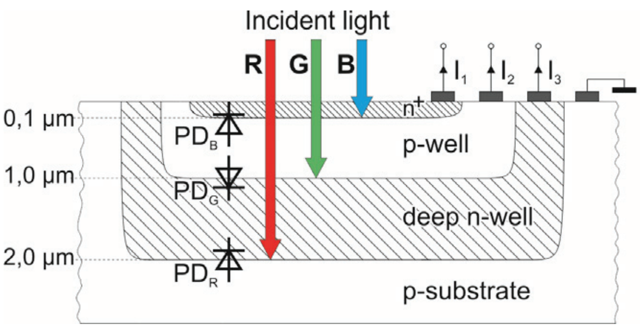
Incident light penetrates into the silicon, is absorbed at a wavelength dependent depth and generates electron-hole pairs. The generation rate G depends thereby on the wavelength λ and the flux Φ_0 of the incident light, the absorption coefficient α of the material and the distance x from the semiconductor surface:

$$G(x, \lambda) = \Phi_0 \alpha(\lambda) e^{-\alpha(\lambda)x} \qquad (1)$$

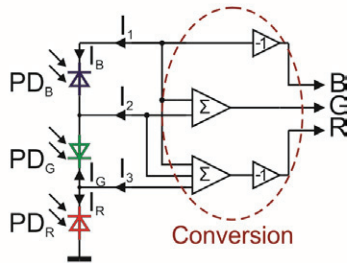
The absorption coefficient and the penetration depths of silicon are highly wavelength dependent over the visible range. Blue light with a wavelength of 400 nm for instance penetrates silicon only up to 0.1 µm while light in the red regime with a wavelength of 650 nm penetrates silicon up to several µm until it is absorbed and electron-hole pairs are generated. Thus the vertical carrier distribution can be used as measurement for the wavelength of the incident light. This principle is used for the triple-junction photodetector.

3. Photodetector design

The detector is built up of three vertically arranged pn junctions as shown in figure 1 (a). The top photodiode consists of source/drain n^+ and p-well and lies in a depth of about 0.1 µm. P-well and deep n-well form the middle photodiode at a depth of 1 µm. The deepest photodiode is built by deep n-well and p-substrate and is located about 2 µm below the surface. The vertical locations of the three junctions are given by the used technology. Nevertheless the three junction depths are corresponding to different



(a)



(b)

Fig. 1: Crosscut (a) and equivalent circuit (b) of triple-junction photodetector

wavelengths – the top pn junction corresponds to a wavelength of around 450 nm (blue), the middle junction corresponds to a wavelength of 580 nm (green) and the deep substrate diode corresponds to a wavelength of 700 nm. Thus the output currents of the three photodiodes are proportional to the blue, the green and the red part of the incident light.

4. Measured results

4.1. Responsivity

In a first step the responsivity of the three junctions was measured. As wavelength-variable light source a 175 W short-arc xenon lamp with broadband output followed by a Digikröm CM110 monochromator was used. The wavelength of the incident light was stepped from 400 nm to 900 nm in 10 nm wavelength steps and the three resulting output currents I_1, I_2 and I_3 were measured. Due to the fact that the top and the middle diode are using a common anode while the middle and the deep diode are using a common cathode the three photocurrents I_R, I_G and I_B cannot be read out directly (figure 1 (b) shows the equivalent circuit). Therefore I_1, I_2 and I_3 are converted by simple conversion algorithms (2), (3) and (4) into the RGB current triple I_R, I_G and I_B:

$$I_R = -(I_1 + I_2 + I_3) \tag{2}$$

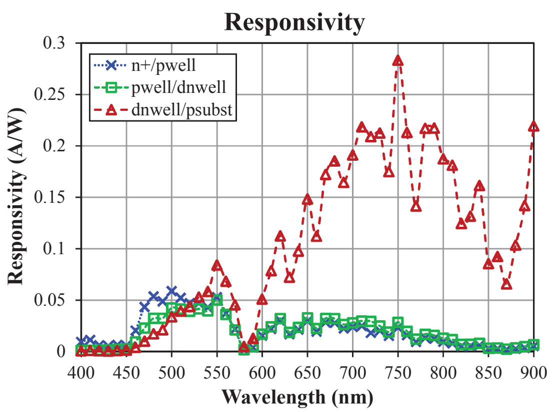
$$I_G = I_1 + I_2 \tag{3}$$

$$I_B = -I_1 \tag{4}$$

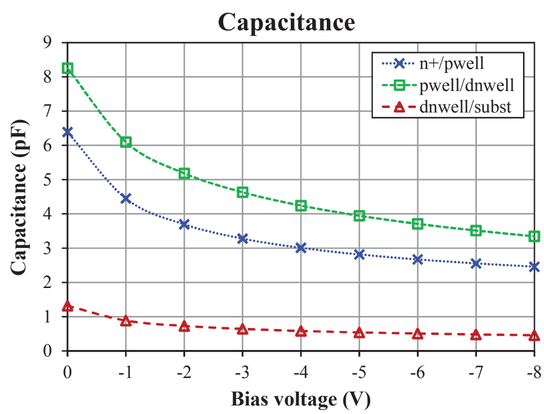
The measured responsivity curves of the three vertically stacked photodiodes are shown in figure 2 (a). The top junction has its maximum responsivity at a wavelength of around 480 nm (blue) while the middle diode has the highest responsivity at 550 nm (green) and the deep diode at 750 nm (IR).

4.2. Capacitance

The capacitance of the three pn junctions was measured with a HP 4284A LCR meter. Figure 2 (b) shows the capacitance of the three different pn junctions against the applied bias voltage.



(a)



(b)

Fig. 2: Measured responsivity (a) and junction capacitance (b) of the 80×80 µm² triple-junction photodetector

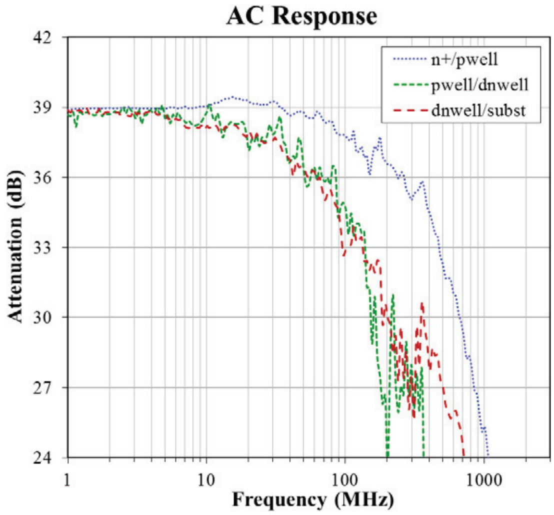


Fig. 3: Measured AC response of the top, the middle and deep pn junction

4.3. AC response

The frequency responses of the three pn junctions were measured by using a modulated 650 nm laser source. The 3 dB-cutoff frequency of the top diode was found at 264 MHz. The bandwidths of the middle and the deep diode indicate maximum data rates of up to 150 Mbit/s. Figure 3 shows the measured frequency response of the three pn junctions.

5. Conclusion

A vertically stacked integrated triple-junction photodetector, fabricated in standard 90 nm CMOS technology without additional color filters was designed and explored in the wavelength range from 400 nm to 900 nm. Measurements show that the sensor can perform color detection and wavelength demultiplexing with data rates up to 150 Mbit/s.

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